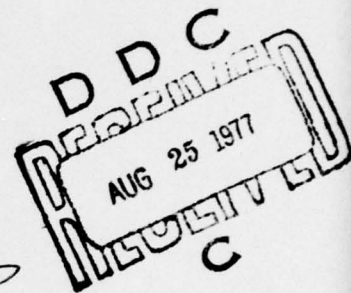| OF |
AD.
A043 290

END
DATE
FILMED

9—77

DDC

CEEDO-TR-77-3

(7)

A THEORY ON WATER FILTRATION
PART III- SENSITIVITY ANAYLSIS, DATA
EVALUATION AND CONCLUSIONS

DET 1 HQ ADTC/ECW
TYNDALL AFB, FLORIDA 32403

JANUARY 1977

FINAL REPORT FOR PERIOD
JUNE 1973- DECEMBER 1976

DDC
AUG 25 1977

Approved for public release; distribution unlimited

CEEDO

CIVIL AND ENVIRONMENTAL
ENGINEERING DEVELOPMENT OFFICE

(AIR FORCE SYSTEMS COMMAND)
TYNDALL AIR FORCE BASE
FLORIDA 32403

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CEEDO-TR-77-3	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A THEORY ON WATER FILTRATION, PART III. SENSITIVITY ANALYSIS, DATA EVALUATION AND CONCLUSIONS		5. TYPE OF REPORT & PERIOD COVERED Final rept. 1 Jun 1973 - 31 Dec 1976
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Stephen P. Shelton, Capt, USAF, BSC		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Det 1 HQ ADTC/ECW Tyndall AFB FL 32403		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 21036W45 6W
11. CONTROLLING OFFICE NAME AND ADDRESS Det 1 (CEEDO) HQ ADTC Tyndall AFB FL 32403		12. REPORT DATE 9 January 1977
		13. NUMBER OF PAGES 37
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

63723F

DDC

AUG 25 1977

C

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in DDC

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Environmental Engineering; Filtration; Mass Transfer; Diffusion; Pressure Drop.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The specific objective of this investigation was to apply existing theoretical concepts used in aerosol mechanics to various water filtration systems. Once developed, these equations were used to describe the water filtration processes of concern as a function of the characteristics of the fluid, suspended particles, and filter media. It was concluded that the proposed model had the potential to predict the relationship between flow, pressure, time, and efficiency for the data evaluated. In addition, the

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE
1 JAN 73

393 250

model was found to have advantages over current water filtration models since, unlike current models, it considers raw water quality and predicts filtration efficiency.

PREFACE

This report summarizes work between 1 July 1973 and
31 December 1976 on Air Force Civil Engineering Center
in-house research job order 21036W45. The project officer
was Stephen P. Shelton, Capt, USAF, BSC.

This report has been reviewed by the Information
Officer (IO) and is releasable to the National
Technical Information Service (NTIS). At NTIS
it will be available to the general public, including
foreign nations.

On 8 April, 1977 AFCEC was reorganized into two
organizations. AFCEC became part of the Air
Force Engineering and Services Agency (AFESA);
the R&D function remains under Air Force Systems
Command as Det 1 (Civil and Environmental Engneer-
ing Development Office-CEEDO) HQ ADTC. Both units
remain at Tyndall AFB FL 32403.

This technical report has been reviewed and is approved
for publication.

STEPHEN P. SHELTON, Capt, USAF, BSC
Water Quality Research Engineer

PETER A. CROWLEY, Maj, USAF, BSC
Director of Environids

DONALD G. SILVA, Lt Col, USAF, BSC
Commander

i

(The reverse of this page is blank)

TABLE OF CONTENTS

iii

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

H = headloss during filtration

H_O = headloss of a clean filter

L_c = thickness of a filter cake

L_s = filter bed depth

T = temperature

C_I = influent supported particle loading

d_{mm} = mass mean particle size

t = time

μ = approach velocity

η_{TA} = average filter efficiency at time t

ρ_p = discrete particle density

ρ_s = density of the media grains

ρ_{BC} = bulk density of the filter cake

ρ_{BS} = bulk density of the graded media

σ_g = log-normal standard deviation

SECTION I

INTRODUCTION

The methods used to accomplish the objectives of this report will be detailed in subsequent sections. The foremost concepts, however, are:

1. to assure that none of the nondefinable or arbitrary variables are highly influential upon the model predictions and,

2. to relate flow, pressure, efficiency, and time predictions made by the models to similar predictions made by other models and observed data.

Comparison between literature data and model predictions may be somewhat less than adequate since most literature data do not contain all variables required for the developed water filtration models. The literature data, however, yield valuable comparative trends from which to draw conclusions about the proposed models.

It is not proposed that the models developed herein ar _____ rrently suitable for industrial application. In _____ TR-77-01 and 77-02 this model was proposed as first _____ ach at converging current design procedures to their underlying common theory. Future research is thus necessary in applied research and data evaluation to provide the parameters necessary to fully evaluate all variables in the theory. The experimental methods for determination of input data are available; however, these methods have not been routinely applied to filtration studies.

SECTION II

DISCUSSION

The sand filtration model developed in CEEDO-TR-77-2 contains a number of conventional and nonconventional inputs. Grain size distribution of the sand bed has long been recognized as an important parameter in sand filter design. Studies of the mechanisms of hydraulic flow in clean sand beds have been the subject of many investigations. (References 1-24). The relationship between sand

1

uniformity and pore clogging has also received much attention. The major developments gained from research in these areas have been the hydraulic theory and the empirical data base for filter performance. Conversely, data inputs required for efficiency prediction as a function of suspended particle/fluid characteristics are drawn from research in aerosol mechanics. (References 25-39). Thus data inputs required in both research areas are necessary for use of the proposed model.

Additional data required is common to both the water filtration and aerosol mechanics research fields. The major analogous inputs include flow rate and filter media depth. Classical water filtration models depart at this point to empirical observation for coefficients to predict filter performance. Some of these models vaguely consider influent water quality through turbidity; however, turbidity is an obscure, nonspecific parameter that is far from satisfactory as a quantitative measure of influent suspended particle characteristics.

The proposed model requires a detailed input of the characteristics of the suspended particles. The suspended particles must be described in terms of concentration per unit volume of water, mean size, size distribution, bulk packing density, and discrete particle density. These parameters are evaluated in a procedure similar to that used in the sand bed characterization. Because suspended particles may be at low concentrations in the fluid and be very small when compared to the sand grains, special techniques may be required to fully evaluate the necessary characteristics. The special techniques required become more sophisticated as the mean particle size decreases. The methodology of these techniques has already been documented. (Reference 40).

Since the pressure drop equation for air filtration theory, as applied to water filtration systems, is similar to the classic Carman-Kozeny equation from which most of the current water filtration models are derived, a detailed parameter study of the pressure drop expression alone is unnecessary. (References 6, 7). The relationships between particle load, pressure drop, and filter efficiency, however, do require a parameter investigation since current water filtration models depart from theory at this point and rely upon empirical information.

2

The proposed water filtration model applies theoretical concepts that relate flow, pressure, time, and efficiency. Representative predictions for pressure drop as a function of time for a given set of fluid, particle, and media conditions are shown in Figures 1 and 2. The fluid conditions indicated on the figures are defined as water at 20°C and flow velocities corresponding to 2, 4, and 6 gallons per square foot per minute (0.1358, 0.2716, and 0.4075 cm/sec). The suspended particles are defined as 10 µm on Figures 1 and 2. The fluid conditions indicated on the figures are defined as water at 20°C and flow velocities corresponding to 2, 4, and 6 gallons per square foot per minute (0.1358, 0.2716, and 0.4075 cm/sec). The suspended particles are defined as 10 µm on Figure 1 and 20 µm on Figure 2 mass mean diameters; the other particle parameters are the same for both figures. These include log-normal standard deviation of 2.0, a bulk density of 0.75 g/cm³, a discrete particle density of 1.5 g/cm³, and a concentration of 15 mg/l. The sand bed characteristics for both figures are constant; these characteristics include a log-normal standard deviation of 1.5, a mass mean sand grain diameter of 800 µm, a bulk density of 1.10 g/cm³ with a maximum bulk density of 1.60 g/cm², and a sand bed depth of 12.5 cm.

As one would expect, the pressure drop is inversely proportional to both mean particle size and flow velocity. This concept is evident from the theory developed herein; however, the currently used water filtration models provide no means of prediction since suspended particles are included as an empirical correction factor. The shape of the curves and their demonstrated relationship between particle size and pressure drop further substantiate the belief that disparities in current water filtration theory are associated with subtle changes in the suspended particle characteristics of the filter influent. Although the size range chosen for demonstration in Figures 1 and 2 was arbitrary, substantial evidence in the literature shows that the 10 µm to 30 µm mass mean size range is typical for raw natural waters and sand filter influents after standard flocculation and sedimentation water treatment processes. (References 15, 25, 27, 41).

In further discussion of Figures 1 and 2 the relationship between slope and flow rate requires evaluation. One might expect that a simple linear relationship exists

3

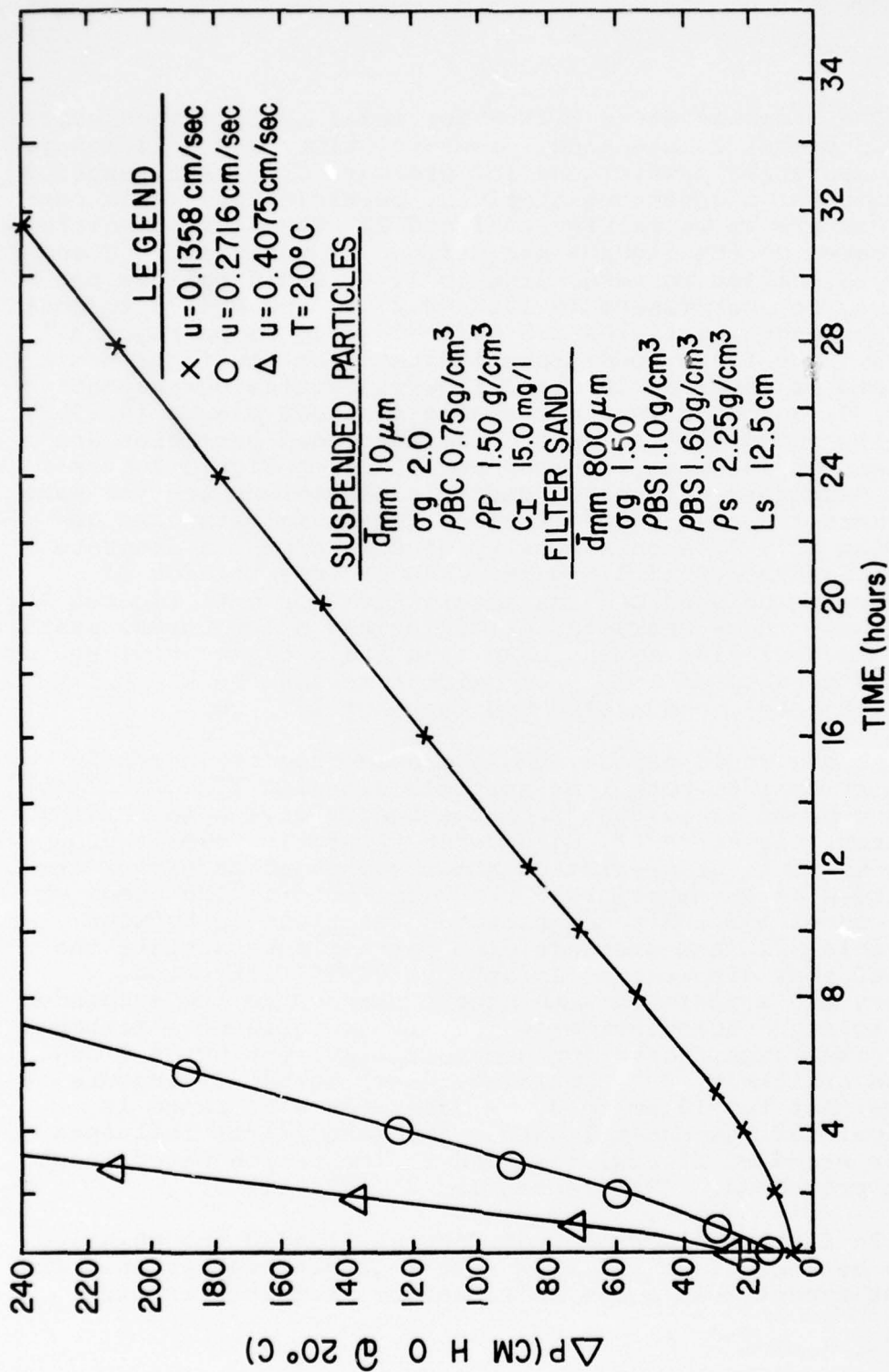Figure 1. Pressure Drop as a Function of Filtration Time for a Graded Media Filtering 10 μm Mass Mean Diameter Particles

4
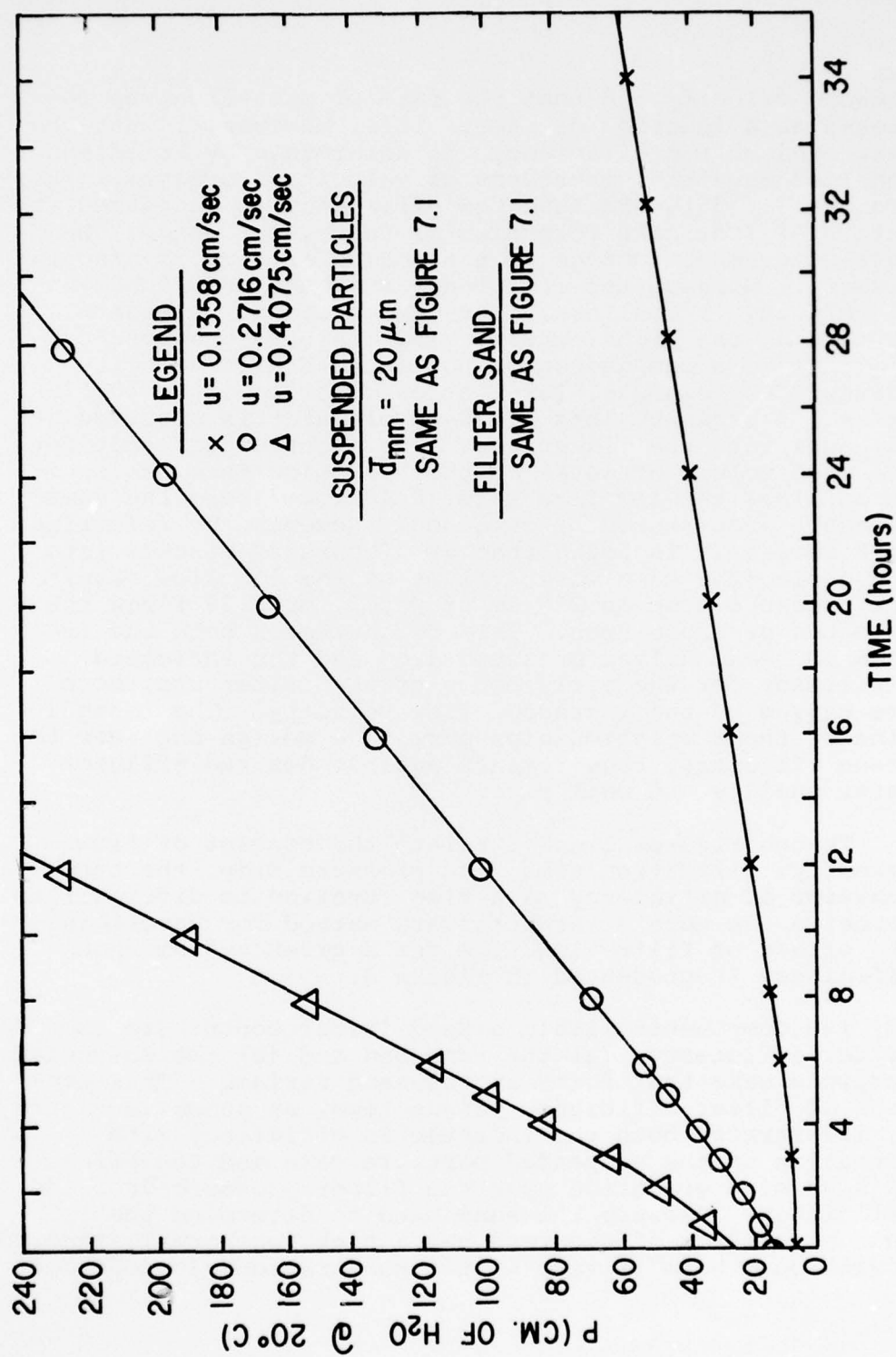
Figure 2. Pressure Drop as a Function of Filtration Time for a Graded Media Filtering 20 μm Mass Mean Diameter Particles

5

between velocity and that the rate of pressure drop increase as a function of time. This, however, is not the case because the efficiency, as determined by Friedlander's modified equation, increases as velocity increases. (References 34, 35). Because the efficiency is increased, the rate of filter cake formation is increased; hence, the rate of pressure change as a function of time is also increased. Because the efficiency increase as a function of velocity is nonlinear, the curves cannot be superimposed as one might expect. This is best observed on Figure 1 by a comparison of the low and high velocity curves. For example, for the low velocity curve (0.1358 cm/sec) a pressure loss of 70 cm of water is observed at 10 hours into the filter run. One might expect that for the same volume of water at the high flow rate, which is three times the low flow rate (0.4075 cm/sec), the same pressure drop should be obtained. However, by referring to Figure 1 it is found that at 3 hours 20 minutes into the cycle (the same water volume as the low flow rate) the pressure drop is 235 cm of water, or 3.36 times the expected pressure drop. This demonstrates both the increased clean filter pressure drop and the increased efficiency for the early hours of the filter run; both are caused by the increased flow velocity. The recognition of these relationships permits a design engineer to trade off energy requirements against desired effluent water quality and unit size.

Though Figures 1 and 2 relate the concept of flow velocity, filtration time, and pressure drop, the true behavior of efficiency as a time function is difficult to perceive. A more straightforward method for describing the effect of filtration time for a given system upon efficiency is presented in Figure 3.

Two components within a sand filter contribute to filter efficiency; (a) the sand bed and (b) the suspended particle cake that forms at the sand surface. This concept of filter efficiency versus time, as shown in Figure 3, illustrates both the increase in efficiency with formation of the suspended particle cake and the effect of sand size gradation upon the filter pressure drop and efficiency. Because the sand used to determine the characteristics of Figure 3 has a high log-normal standard deviation, there is very little penetration of suspended

6

EFFICIENCY (percent)

99.9
99.8
99.6
99.4
99.2
99.0
98.0
96.0
94.0
92.0
90.0
80.0
60.0
40.0
20.0
0

LEGEND
X   10 μm Cake Eff.
△   20 μm Cake Eff.
□   10 μm Sand Eff.
○   20 μm Sand Eff.

SUSPENDED PARTICLE
$\bar{d}_{mm}$ 10μm or 20μm
           As Indicated
σg 2.0
ρ_{BC} 0.75 g/cm^3
ρ_p 1.50 g/cm^3
C_I 15.0 mg/l

FILTER SAND
$\bar{d}_{mm}$ 800μm
σg 1.50
ρ_{BS} 1.10 g/cm^3
ρ_{BS} 1.60 g/cm^3
L_s 12.5 cm

TIME (hours)
2   4   6   8   10   12   14   16   18   20   22
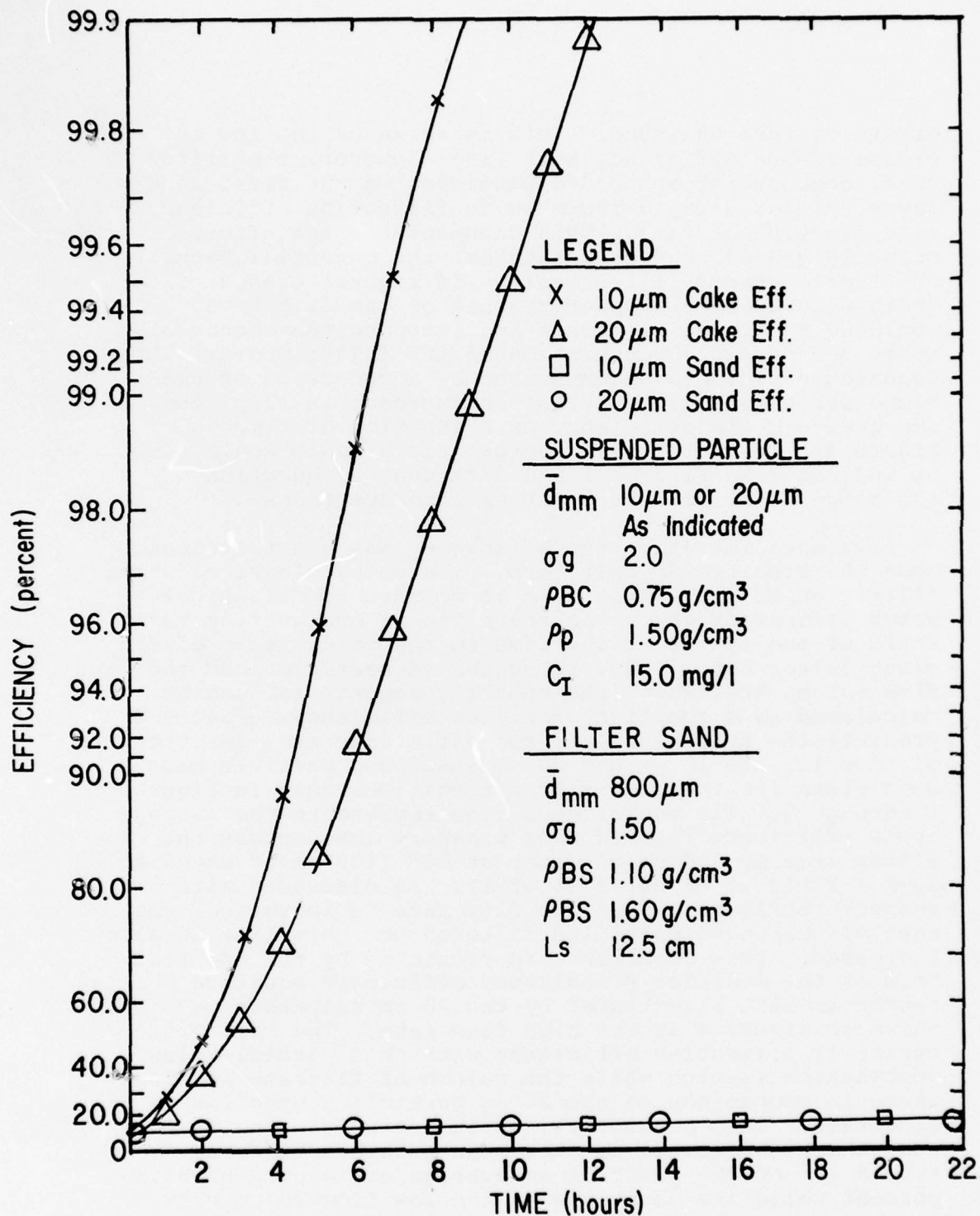
Figure 3.   Graded Media Filter Efficiency as a Function of
             Time for 10 μm and 20 μm Mass Mean Diameter
             Particles

7

particles into the sand. This is shown by the low increase in bed efficiency with time; however, the filter cake, composed of suspended particles on the first sand layer, yields a rapid increase in filtration efficiency as a function of time. This demonstrates the effect of normally graded sand or points out the potential benefit of reverse graded filter media. If reverse graded filter media were used, the upper reaches of the filter bed would be the least efficient and increase the degree of suspended particle penetration of the filter media. This occurrence would be demonstrated by a reduction of the slope for cake efficiency and an increase in slope for the graded media efficiency as a function of time in Figure 3. The described reverse graded media would also be indicated in Figures 1 and 2 through a reduction in the slope of all pressure versus time functions.

Average filtration run efficiency has great influence upon the specific deposit term, σ, used by classical water filtration models. This term is defined for classical water filtration theory as the ratio of the average voids ratio of the filter at any time to the voids ratio of the clean filter bed. Thus, if suspended particle load and flow volume are known, the specific deposit (σ) can be calculated as a function of filter efficiency. Figure 4 predicts the average filter run efficiency as a function of time for the 10 μm and 20 μm suspended particle mass mean sizes for the same filter conditions used in Figures 1 through 3. The end of each line represents the average cycle efficiency reached when pressure loss across the filter exceeds 400 cm of water at 20° (400 cm of water at $20^{\circ}C = 13.12$ ft of water at $68^{\circ}F$). As discussed with respect to Figure 1 when the flow rate is increased, the mass of suspended particles filtered per unit time is also increased. This occurrence is predicted by the inertial term of the modified Friedlander efficiency equation. This factor is best illustrated by the 20 μm suspended particle curve on Figure 4 at the high flow rate. The rate of increase in filtration efficiency with this particle-flow combination is high while the volume of filtrate is also large in comparison to the 20 μm particle at the lower flow rate. This means that, at 50 hours into the filter run, the high flow 20 μm mass mean size has filtered 4.88×10^4 of the fluid at an average efficiency of 98.5 percent while its counterpart, the low flow 20 μm mass
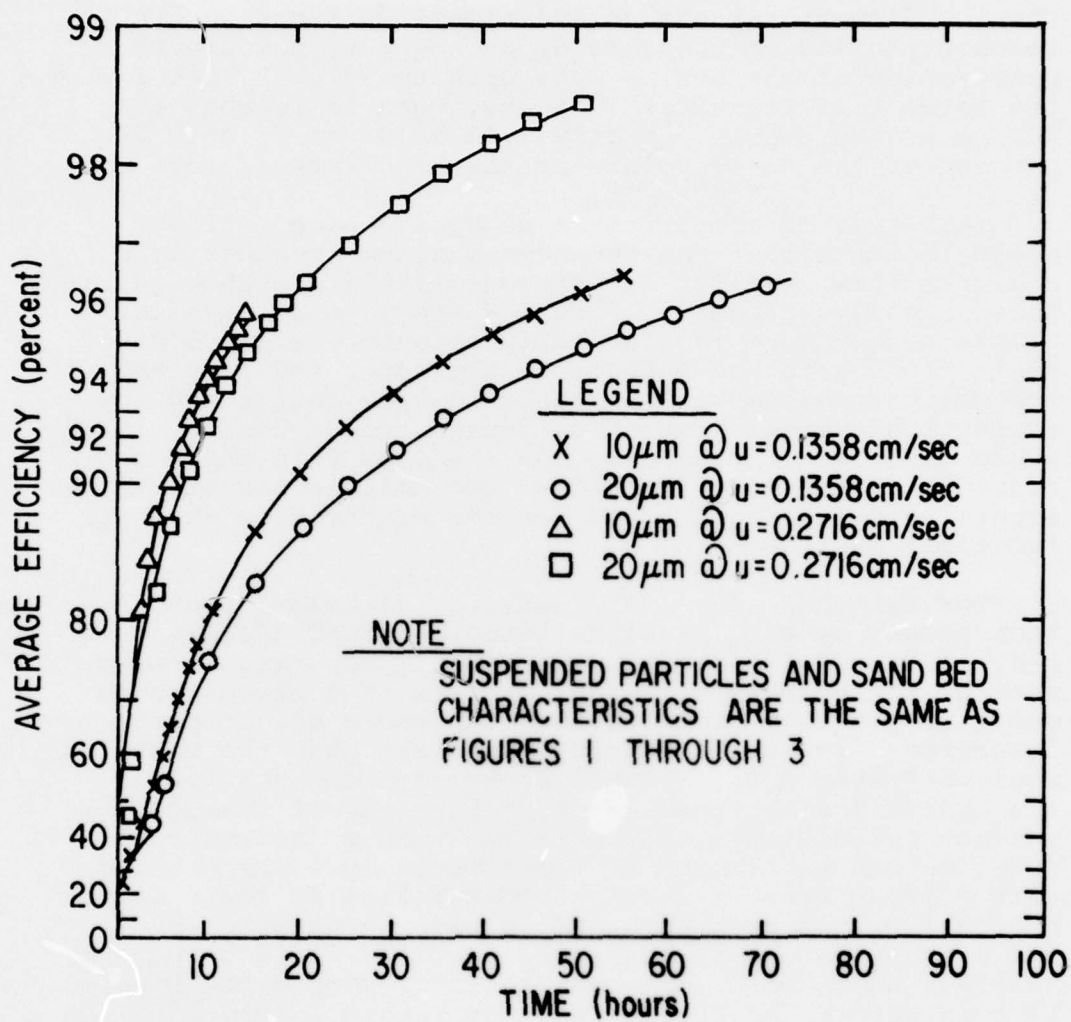
8

Figure 4.   Average Graded Media Filter Efficiency as a Function of Time

9

mean size, has filtered only 2.44 c 10^4 cm of fluid at an
average efficiency of 94.8 percent. In addition, the high
flow filter has reached 400 cm of pressure drop at 50 hours,
the low flow filter has an additional 20 hours before it
reaches its 400 cm pressure drop; however, because the
penetration of the bed is less with the slower rate filter,
the total filtrate after 70 hours, when it reaches the
400 cm pressure drop, is only 3.42 x 10^4 cm or only 70
percent of the total volume of the high rate filter.

This type of comparison made by a design engineer
would indicate that for the same maximum pressure loss,
a higher flow, smaller filter would yield a higher quality,
less expensive product. Figure 4 provides an excellent
sample of how more theoretically oriented filter designs
could yield great advantages to the water industry and to
the design engineer. The reason is straightforward be-
cause with current filtration design techniques the filter
would have been designed at the low flow rate which cor-
responds to the rule of thumb - two gallons per minute per
square foot (gpm/sq ft) and not the higher rate which is
two times that loading.

The Carman-Kozeny (References 6, 7) relationship has
been shown, by many previous investigations (References
1-4, 11-14, 42-53), to be a reasonably accurate measure-
ment of the hydraulic characteristics of a clean graded
media if the characteristics of the media are properly
described. It has also been shown that when the media is
used to filter a water laden with suspended particles,
the hydraulics continue to be predictable if the specific
surface relationship in the Carman-Kozeny (References 6, 7)
equation can be determined experimentally. The problem
with current water filtration models lies in their failure
to consider the change in filter bed characteristics from
the standpoint of the suspended particle-fluid suspension;
this has been the primary parameter developed and studied
in this paper. As demonstrated by Figure 1 through 4 the
mass mean particle size, distribution, and the rate of
flow are predictable and realistic in their effect upon
filter efficiency and pressure drop.

Because there has been little interest in filter
efficiency in the literature and the methods used currently
by water filtration theory do not require suspended

10

particle size information for their headloss predictions, little data are available incorporating all of the required information for model validation. Model validation must thus be performed by alteration of the prediction parameters in the air filtration theory for water application.

Many of the headloss theories in filtration are presented in terms of the ratio of headloss at time t to initial headloss plotted as a function of σ, the specific deposit. Most water models assume that σ is uniform throughout the bed penetration depth. In reality, a concentration gradient of particles must exist; thus, σ is actually an average term for the penetration depth. Using this definition and the air theory for water application model, the value of σ in the context of water researchers can be calculated:

$$\sigma = \frac{C_I \, u \, t}{L_C \, \rho_{BC}} \, \eta_{TA} \qquad (1)$$

where σ is the specific deposit, C_I is the suspended particle concentration of the influent, u is the filtration velocity, t is time, L_C is the sand bed thickness, ρ_{BC} is the bulk density of the sand bed, and η_{TA} is the average filter efficiency at time t into the filter run. The headloss ratio is the ratio of the headloss at some time in the filter run to the headloss of the clean sand bed for a constant velocity. This ratio can be calculated at any time during the filter run by the proposed water filtration model.

Using the headloss ratio and specific deposit, Figure 5 was developed to compare current water filtration models to the proposed water filtration model. The hatched area in Figure 5 indicates the range of headloss predictions made by the various classical models considered. (References 5, 14, 54-56). The filter media used for the predictions was assumed to be 800 μm mass mean sand grain diameter with a log-normal standard deviation of 1.5. The flow rate was assumed to be 0.1358 cm/sec (2.9 gpm/sq ft). All of the above assumptions were made by previous investigators (References 5, 14, 54-56) and their respective
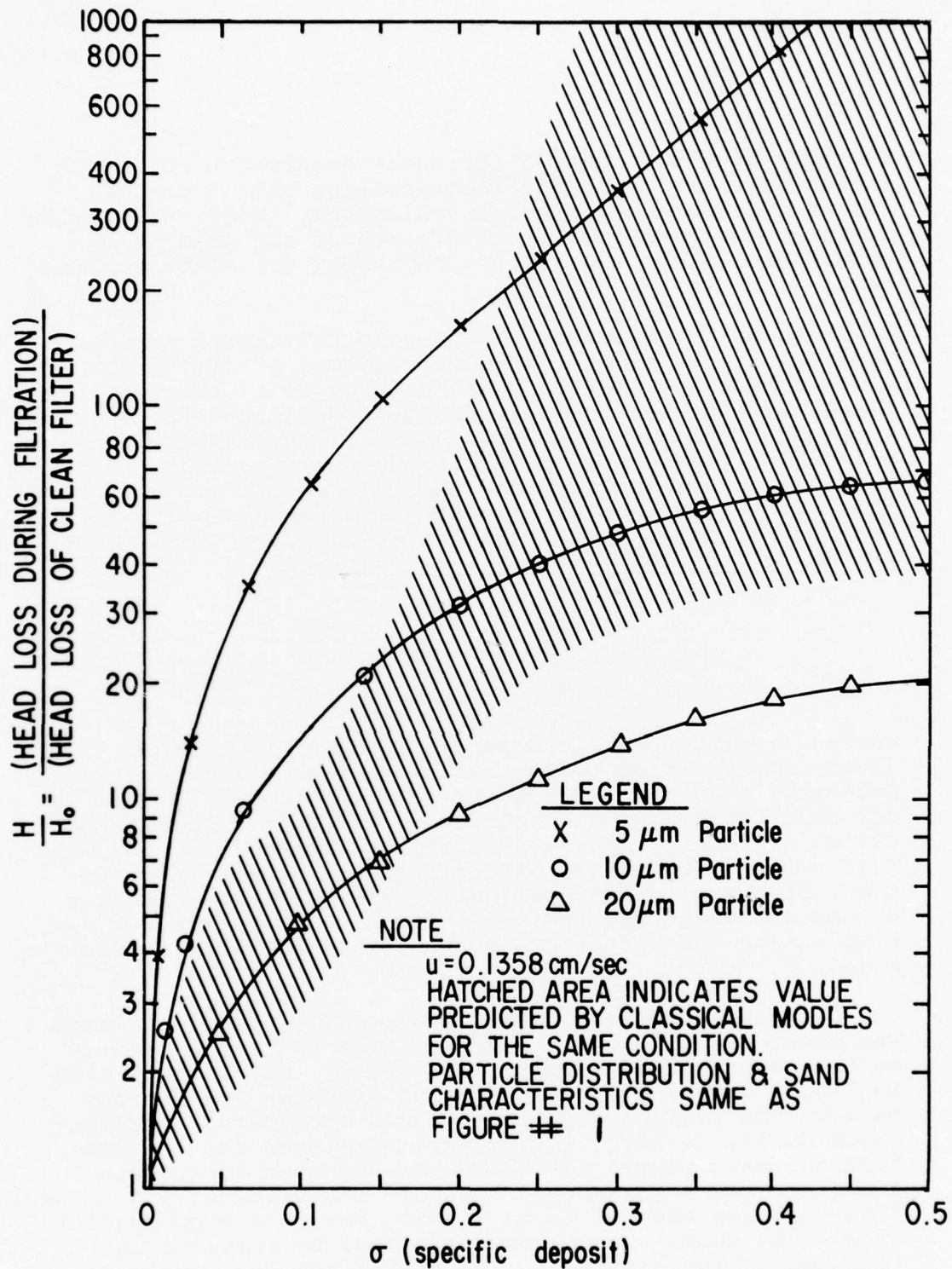
11

Figure 5. Headloss Ratio as a Function of Specific Deposit for 5 μm, 10 μm, and 20 μm Mass Mean Diameter Particles

12

predictions presented in the literature as plots of head-loss ratio as a function of specific deposit. Thus the hatched area in Figure 5 represents the breadth of predictions made by classical models for the above stated filtration conditions.

The above discussed classical models do not require specific data with respect to the suspended particles; they require only nonspecific descriptions of the water quality such as turbidity. For this reason no data were obtained by these investigations (References 5, 14, 54-56) with respect to suspended particle size or size distribution. For the same reason typical values of mass mean particle size were assumed with a log-normal standard deviation of 2.0. The particle sizes used in the headloss predictions as well as the distribution of sizes were typical values from the literature (References 15, 25, 29, 41) for natural waters of flocculated and settled water treatment plant effluents.

Examination of Figure 5 reveals that the rate of pressure drop increase is inversely proportional to particle size. This is the expected result because smaller particles tend to form less porous cake structures. The middle ground for predictions made by the current water filtration theory indicates a mass mean particle size range, if predicted by the new model, to be between 10 μm and 20 μm. Although suspended particle size determinations were not made by the investigators proposing the headloss equations that form the hatched area in Figure 5, there is substantial evidence in the literature that the suspended particles, in most natural waters and/or micro-floc carryover from chemical pretreated process, fall in the general mass mean size range between 10 μm and 20 μm. The indirect conclusion that can be drawn from Figure 5 is that a model which considers the influent suspended particle characteristics is at least as valid as the current water filtration models. Because this model predicts the relationship between pressure, flow, time, and efficiency from the basic characteristics of the system, great benefits could be accrued from its use in the design of filtration systems for atypical waters.

Current water filtration design models are not concerned with efficiency. Therefore, data to this end are

normally not directly associated with filtration research. For this reason the best available data characterizes the media, suspended particles (to various degrees), and efficiency, but unfortunately it does not relate pressure drop and time. However, if it is assumed that the validation presented by Figure 5 is sufficient to indicate a reasonable relationship between particle size and pressure, time, flow, and efficiency and if it is further assumed that the Carman-Kozeny pressure drop equation is reasonably accurate, then inferences with respect to efficiency from data that does not contain headloss information can be made.

Tables 1 through 8 present filter efficiency data for graded media filter systems from studies presented in the literature (References 57-61). These data consider graded media systems that use sand, anthracite, and spherical glass media components to filter a variety of fluid/particle suspensions. Particle size and distribution characteristics for the suspensions were not given by the investigators whose data comprise the tables; however, a consistent set of characteristic values was used for each particle type (i.e., iron floc and alum floc). Furthermore, the values assumed are in the range of those described by previous investigators (References 15, 25, 27, 41) as typical for the suspensions under consideration. These typical values were used for both the iron and alum floc particles. Although the predictions of the new model are not always precise, all cases in Tables 1 through 8 agree to a reasonable degree. The comparisons made in these tables seem to indicate the validity of the model and show promise for its use as a filtration design tool.

In addition to the data presented in Tables 1 through 8, efficiency data from the virus removal literature were also analyzed. (Reference 57). Although the predictions made by the model in these areas were sometimes reasonable, it was determined that, because the virus particles are virtually mono-dispersed, mono-changed, and in the sub-0.1 μm size range, any conclusions with respect to removal efficiency would be conjecture, due to the increased electrophoretic effect. A possible future research area, however, could consider collection efficiency in this range, modifying the Friedlander equation to consider electrophoretic mobility.

14

TABLE 1.   COMPARISON OF LITERATURE DATA FROM REFERENCE 61
FOR SAND FILTRATION EFFICIENCY WITH PREDICTIONS
FROM THIS INVESTIGATION FOR NON-SPHERICAL SAND PARTICLES

Investigation	Reference 61	This Investigation
Material	Sand	Sand
Filter depth (cm)	2.86[a]	2.90[b]
Porosity of material	0.41[a]	0.41[b]
Sphericity	0.86[b]	1.00[b]
Filtration rate (cm/sec)	0.347[a]	0.347[b]
Temperature(^{o}C)	20.0[a]	20.0[b]
Sand Bed: mass mean size (μm)	700.0[a]	700.0[b]
Log-normal standard deviation	1.0[a]	1.0[b]
Type of suspension	Iron floc[a]	Iron floc[b]
Suspended particles:		
Mass mean size (μm)	d	30.0[b]
Log-normal standard deviation	d	2.0[b]
Concentration influent	2.8[a] (mg/1)	2.8[b] (mg/1)
Concentration effluent	2.15[a] (mg/1)	1.84[c] (mg/1)
Filter efficiency (%)	22.3[a]	34.3[c]
Filtration time (min)	10[a]	10[b]

[a] measured by this or referenced investigation

[b] assumed by this or referenced investigation

[c] predicted by this investigation

[d] not reported by referenced investigation

15

TABLE 2. COMPARISON OF LITERATURE DATA FROM REFERENCE 59
FOR SAND FILTRATION EFFICIENCY WITH PREDICTIONS
FROM THIS INVESTIGATION FOR 723 μm MASS SAND SIZE

Investigation	Reference 59	This Investigation
Material	Sand	Sand
Filter depth (cm)	76.2[a]	76.2[b]
Porosity of material	0.41[a]	0.41[b]
Sphericity	0.86[b]	1.00[b]
Filtration rate (cm/sec)	0.347[a]	0.347[b]
Temperature (^{o}C)	20.0[a]	20.0[b]
Sand bed: mass mean size (μm)	723.0[a]	723.0[b]
Log-normal standard deviation	1.51[a]	1.51[b]
Type of suspension	Alum floc[a]	Alum floc[b]
Suspended particles:		
Mass mean size (μm)	d	10.0[b]
Log-noraml standard deviation	d	1.8[b]
Concentration influent	2.5[a] (JTU)	2.5[b] (mg/1)
Concentration effluent	0.2[a] (mg/1)	0.16[c] (mg/1)
Filter efficiency (%)	92.0[a]	93.7[b]
Filtration time (min)	615[a]	600[b]

[a]measured by this or referenced investigation

[b]assumed by this or referenced investigation

[c]predicted by this investigation

[d]not reported by referenced investigation

16

TABLE 3. COMPARISON OF LITERATURE DATA FROM REFERENCE 59
FOR SAND FILTRATION EFFICIENCY WITH PREDICTIONS
FROM THIS INVESTIGATION FOR 170 μm MASS MEAN SAND SIZE

Investigation	Reference 59	This Investigation
Material	Sand	Sand
Filter depth (cm)	76.2[a]	76.2[a]
Porosity of material	0.41[a]	0.41[b]
Sphericity	0.86[b]	1.00[b]
Filtration rate (cm/sec)	0.347[a]	0.347[b]
Temperature (°C)	20.0[a]	20.0[b]
Sand bed: mass mean size (μm)	170.0[a]	170.0[b]
Log-normal standard deviation	1.66[a]	1.66[b]
Type of suspension	Alum floc[a]	Alum floc[b]
Suspended particles:		
Mass mean size (μm)	d	10.0[b]
Log-normal standard deviation	d	2.1[b]
Concentration influent	2.3[a] (JTU)	2.3[b] (mg/1)
Concentration effluent	0.39[a] (mg/1)	0.50[c] (mg/1)
Filter efficiency (%)	83.0[a]	78.3[c]
Filtration time (min)	204[a]	240[b]

[a]measured by this or referenced investigation

[b]assumed by this or referenced investigation

[c]predicted by this investigation

[d]not reported by referenced investigation

17

TABLE 4. COMPARISON OF LITERATURE DATA FROM REFERENCE 60
FOR SAND FILTRATION EFFICIENCY WITH PREDICTIONS
FROM THIS INVESTIGATION FOR 0.347 cm/sec FILTRATION RATE

Investigation	Reference 60	This Investigation
Material	Sand	Sand
Filter depth (cm)	121.92^a	121.92^b
Porosity of material	0.43^a	0.43^b
Sphericity	0.86^b	1.00^b
Filtration rate (cm/sec)	0.347^a	0.289^b
Temperature (^{o}C)	20.0^a	20.0^b
Sand bed: mass mean size (μm)	100.0^a	1000.0^b
Log-normal standard deviation	1.0^a	1.0^b
Type of suspension	Iron floc^a	Iron floc^b
Suspended particles:		
Mass mean size (μm)	d	30.0^b
Log-normal standard deviation	d	2.0^b
Concentration influent	3.4^a (mg/1)	3.5^b (mg/1)
Concentration effluent	0.05^a (mg/1)	0.0497^c (mg/1)
Filter efficiency (%)	98.57^a	98.58^c
Filtration time (min)	1068^a	1080^b

[a]measured by this or referenced investigation

[b]assumed by this or referenced investigation

[c]predicted by this investigation

[d]not reported by referenced investigation

18

TABLE 5. COMPARISON OF LITERATURE DATA FROM REFERENCE 61
FOR SAND FILTRATION EFFICIENCY WITH PREDICTIONS
FROM THIS INVESTIGATION FOR SPHERICAL SAND PARTICLES

Investigation	Reference 61	This Investigation
Material	Sand	Sand
Filter depth (cm)	2.86[a]	2.86[b]
Porosity of material	0.37[a]	0.37[b]
Sphericity	1.00[b]	1.00[b]
Filtration rate (cm/sec)	0.347[a]	0.347[b]
Temperature (^{o}C)	20.0[a]	20.0[b]
Sand bed: mass mean size (μm)	700.0[a]	700.0[b]
Log-normal standard deviation	1.0[a]	1.0[b]
Type of suspension	Iron floc[a]	Iron floc[b]
Suspended particles:		
Mass mean size (μm)	d	30.0[b]
Log-normal standard deviation	d	2.0[b]
Concentration influent	2.2[a] (mg/1)	2.2[b] (mg/1)
Concentration effluent	1.45[a] (mg/1)	1.45[c] (mg/1)
Filter efficiency (%)	34.1[a]	34.1[c]
Filtration time (min)	4[a]	4[b]

[a]measured by this or referenced investigation

[b]assumed by this or referenced investigation

[c]predicted by this investigation

[d]not reported by referenced investigation

19

TABLE 6.   COMPARISON OF LITERATURE DATA FROM REFERENCE 59
FOR SAND FILTRATION EFFICIENCY WITH PREDICTIONS
FROM THIS INVESTIGATION FOR 660 μm MASS MEAN SAND SIZE

Investigation	Reference 59	This Investigation
Material	Sand	Sand
Filter depth (cm)	76.2[a]	76.2
Porosity of material	0.37[a]	0.37
Sphericity	1.00[a]	1.00
Filtration rate (cm/sec)	0.347[a]	0.347
Temperature (^{o}C)	20.0[a]	20.0
Sand bed: mass mean size (μm)	660.0[a]	660.0
Log-normal standard deviation	1.43[a]	1.43
Type of suspension	Alum floc[a]	Alum floc
Suspended particles:		
Mass mean size (μm)	d	10.0
Log-normal standard deviation	d	1.8
Concentration influent	2.4[a] (JTU)	2.4 (mg/1)
Concentration effluent	1.21[a] (mg/1)	0.358 (mg/1)
Filter efficiency (%)	91.2[a]	85.1
Filtration time (min)	453[a]	480.0

[a]measured by this or referenced investigation

[b]assumed by this or referenced investigation

[c]predicted by this investigation

[d]not reported by referenced investigation

TABLE 7. COMPARISON OF LITERATURE DATA FROM REFERENCE 59
FOR SAND FILTRATION EFFICIENCY WITH PREDICTIONS
FROM THIS INVESTIGATION FOR 1694 µm MASS MEAN SIZE

Investigation	Reference 59	This Investigation
Material	Sand	Sand
Filter depth (cm)	76.2[a]	76.2[b]
Porosity of material	0.51[a]	0.51[b]
Spericity	0.63[a]	1.00[b]
Filtration rate (cm/sec)	0.347[a]	0.347[b]
Temperature (^{o}C)	20.0[a]	20.0[b]
Sand bed: mass mean size (µm)	1694[a]	1694[b]
Log-normal standard deviation	1.76[a]	1.76[b]
Type of suspension	Alum floc[a]	Alum floc[b]
Suspended particles:		
Mass mean size (µm)	d	10.0[b]
Log-normal standard deviation	d	2.1[b]
Concentration influent	2.6[a] (JTU)	2.6[b] (mg/1)
Concentration effluent	0.40[a] (mg/1)	0.24[c] (mg/1)
Filter efficiency (%)	84.6[a]	90.8[c]
Filtration time (min)	300.0[a]	300.0[b]

[a]measured by this or referenced investigation

[b]assumed by this or referenced investigation

[c]predicted by this investigation

[d]not reported by referenced investigation

21

TABLE 8. COMPARISON OF LITERATURE DATA FROM REFERENCE 60
FOR SAND FILTRATION EFFICIENCY WITH PREDICTIONS
FROM THIS INVESTIGATION FOR 0.289 cm/sec FILTRATION RATE

Investigation	Reference 60	This Investigation
Material	Sand	Sand
Filter depth (cm)	121.9[a]	121.9[b]
Porosity of material	0.54[a]	0.54[b]
Sphericity	0.63[a]	1.00[b]
Filtration rate (cm/sec)	0.289[a]	0.289[b]
Temperature (^{O}C)	20.0[a]	20.0[b]
Sand bed: mass mean size (μm)	1000[a]	1000[b]
Log-normal standard deviation	1.0[a]	4.0[b]
Type of suspension	Iron floc[a]	Iron floc[b]
Suspended particles:		
Mass mean size (μm)	d	30.0[b]
Log-normal standard deviation	d	2.0[b]
Concentration influent	3.5[a] (mg/l)	3.5[b] (mg/l)
Contration effluent	0.08[a] (mg/l)	0.02[c] (mg/l)
Filter efficiency (%)	97.7[a]	99.7[c]
Filtration time (min)	1524[a]	1560[b]

[a]measured by this or referenced investigation

[b]assumed by this or referenced investigation

[c]predicted by this investigation

[d]not reported by referenced investigation

22

Parameters and data have been evaluated for the sand filtration model derived from water and air filtration theory. It has been shown, as presupposed, that the physical characteristics and concentration of the suspended particles are influential in the performance of graded media filters, with respect to the relationships between pressure, flow, time, and efficiency. Furthermore, data with respect to the hydraulic characteristics and filter efficiency have been presented that substantiate the merit of the proposed model. The model requires further testing before confidence can be placed in all aspects of its performance. It is felt, however, that the foundation for a new approach for sand filtration modeling has been built.

SECTION III

CONCLUSIONS

The use of combined air and water filtration theory has been considered by this investigation. Theoretical concepts from aerosol mechanics were successfully modified for use in water-oriented systems. From these concepts a filtration model was proposed to predict the interrelationship between flow, pressure, time, and efficiency for graded media water filters. These models were subsequently tested from the standpoint of their interrelated parameters and their applicability to filtration data in the literature.

The proposed sand filtration model demonstrated a potential to predict the relationship between flow, pressure, time, and efficiency. Data validation of this model indicated that its predictions were within the range of predictions made by classical water filtration models for typical data ranges. It was further shown that the new model could adequately predict filter efficiency for a wide range of fluid/particle suspensions and filter media described in the literature. It was concluded that the new model offered a twofold advantage over classical models in that it (a) considers the suspended particles quantitatively and (b) it can predict the filter efficiency.

REFERENCES

1. Baylis, J. "Experiences in Filtration", *Journal American Water Works Association*, 29:8:1010, 1937.

2. Baylis, J. "Seven Years of High-Rate Filtration", *Journal, American Water Works Association*, 48:3:585, 1956.

3. Baylis, J. "Nature and Effects of Filter Backwashing", *Journal, American Water Works Association*, 51:1:129, 1959.

4. Baylis, J. "Design Criteria for Rapid Sand Filters", *Journal, American Water Works Association*, 51:11:1443, 1959.

5. Camp, I. "Theory of Water Filtration", *American Society of Civil Engineers - Sanitary Engineering Division Journal*, 90:SA4:1, 1964.

6. Carman, P. "Fluid Flow Through Granular Beds". *Transactions of the Institute of Chemical Engineers* (London, England), 15:150, 1937.

7. *Carman, P.* "Fundamental Principles of Industrial Filtration", *Transactions of the Institution of Chemical Engineers*. 16:168, 1938.

8. Carman, P. "The Action of Filter Aids", *Journal of Industrial and Engineering Chemistry*, 30:1163, 1938.

9. Carman, P. "The Action of Filter Aids", *Journal of Industrial and Engineering Chemistry*, 31:1047, 1939.

10. Carman, P. "In Symposium on New Methods for Particle Size Determination in the Subsieve Range", American Society of Testing Materials, Philadelphia, Pennsylvania, 1951.

11. Deb, A. "Discussion", *Proceedings, American Society of Civil Engineers - Sanitary Engineering Division*, 91:SA2 Proc. 4281:84, 1965.

12. Deb, A. "Discussion", Proceedings, American Society of Civil Engineers - Sanitary Engineering Division, 93:SA1 Proc. 4637:321, 1966.

13. Deb, A. "Discussion", Proceedings, American Society of Civil Engineers - Sanitary Engineering Division, 93:SA4 Proc. 5358:124, 1967.

14. Deb, A. "Theory of Sand Filtration", American Society of Civil Engineers - Sanitary Engineering Journal, 95:SA3:399, 1969.

15. Ghosh, G. "Media Characteristics in Water Filtration", American Society of Civil Engineers - Sanitary Engineering Division Journal, 84:SA1, Proc. 1533, 1958.

16. Hazen, R. "Elements of Filter Design," Journal, American Water Works Association, 43:3:208, 1951.

17. Ives, K. "Simulation of Filtration on Electronic Digital Computer", Journal, American Water Works Association, 52"7"933, 1960.

18. Ives, K. "Rational Design of Filters", Proceedings, Institute of Civil Engineers (London), 16:180, 1960.

19. Ives, K. "New Concepts in Filtration", Journal of Water and Wastewater Engineering, 65:307, 1961.

20. Ives, K. "Simplified Rational Analysis of Filter Behavior", Proceedings, Institute of Civil Engineers (London), p. 345, 1963.

21. Ives, K. "A Theory of the Functioning of Deep Filters", Proceedings of the Symposium on Interaction Between Fluids and Particles, Institute of Chemical Engineers (London), p. 260, 1964

22. Ives, K. "Progress in Filtration", Journal, American Water Works Association, 56:9:1226, 1964.

23. Ives, K. and I. Sholji. "Research on Variables Affecting Filtration", American Society of Civil Engineers - Sanitary Engineering Division Journal, 491:SA4, Proc. 4436:1, 1965.

24. Ives, K. and J. Gregory, "Surface Forces in Filtration", _Proceedings, Society of Water Treatment and Examination_, 15:92, 1966.

25. Cadle, R. _Particle Size Theory and Industrial Applications_. New York: Reinholt Publishing Company, 1965.

26. Chen, C. "Filtration of Aerosols by Fibrous Media", _Chemical Review_, 55:595, 1955.

27. Davies, C. "Symposium of Particle Size Analysis", _Transactions, Industrial Chemical Engineers and Society of Chemical Industry_ p. 25, 1947.

28. Davies, C. "Technical Note", _Proceedings of Physics Society of London_, 57:259, 1950.

29. Davies, C. "Technical Note", _Proceedings of Physics Society of London_, 63B:288, 1950.

30. Davies, C. "Technical Note", _Proceedings of Institute of Mechanical Engineers of London_, 1B:185, 1952.

31. Davies, C. "Problems in Aerosol Filtration", _Filtration and Separation_ (Great Britain), 7:6:692, 1970.

32. Davies, C. _Air Filtration_. London: Academic Press, Inc., 1973.

33. Davies, C. and G. Jeffery. "Separation of Droplet Dispersions, Part I. Coalescence of Liquid Droplets", _Filtration and Separation_ (Great Britain), 7:5:546, 1970.

34. Friedlander, S. "Theory of Aerosol Filtration", _Journal, Industrial and Engineering Chemistry_, 50:8:1161, 1958.

35. Friedlander, S. and R. Pascari. "The Efficiency of Fibrous Aerosol Filters", _The Canadian Journal of Chemical Engineers_, p. 212, December 1960.

36. Fuchs, N. A. _The Mechanics of Aerosols_. New York: Pergamon Press, 1964.

37. Racheshkevich, L. "Particle Dynamics," Zh. Fiz. Khim, 32:282, 1958, according to Fuchs, Reference #91.

38. Strauss, W. Industrial Gas Cleaning. New York: Pergamon Press, 1966.

39. Strauss, W. and B. Lancaster. "Prediction of Effectiveness of Gas Cleaning Methods at High Temperatures and Pressures," Journal, Atmospheric Environment, Pergamon Press, 2:135, 1968.

40. Jacobs, S. "The Distribution of Pore Diameters in Graded Filters", Filtration and Separation (Great Britain), 9:525, 1972.

41. Ives, K. "Depth Filtration of Liquids", Filtration and Separation (Great Britain), 7:6:700, 1970.

42. Hsiung, K. and J. Cleasby. "Prediction of Filter Performance", American Society of Civil Engineers - Sanitary Engineering Division Journal, 94:SA6 Proc. 6270:1043, 1968.

43. Hsiung, K. "Filtrability Study on Secondary Effluent Filtration", American Society of Civil Engineers - Sanitary Engineering Division Journal, 98:SA3:505, ;972.

44. Hudson, H. "Factors Affecting Filtration Rates", Journal, American Water Works Association, 48:9:1138, 1956.

45. Hudson, H. "Factors Affecting Filtration Rates", Journal, American Water Works Association, 50:2:271, 1958.

46. Hudson, H. "Operating Characteristics of Rapid Sand Filters", Journal, American Water Works Association, 51:1:114, 1959.

47. Hudson, H. "Declining-Rate Filtration", Journal, American Water Works Association, 51:11:1455, 1959.

48. Tiller, F. "The Role of Porosity in Filtration", Journal, Chemical Engineering Progress, 49:9:467, 1953.

49. Tiller, F. "The Role of Porosity in Filtration", Journal, Chemical Engineering Progress, 51:6:282. 1955.

50. Tiller, F. "The Role of Porosity in Filtration", Journal, American Institute of Chemical Engineers, 4:2:173, 1958.

51. Tiller, F. and H. Cooper. "The Role of Porosity in Filtration", Journal, American Institute of Chemical Engineers, 6:4:595, 1960.

52. Tiller, F. and C. Huang. "Theory-Flow Cake Slurries", Journal, Industrial Engineering Chemistry, 53:7:529, 1960.

53. Tiller, F. "Laboratory Analysis for the Solution of Industrial Filtration Problems", Filtration and Separation (Great Britain), 7:4:430, 1970.

54. Mackrle, V. and S. Mackrle. "Adhesion in Filters", American Society of Civil Engineers - Sanitary Engineering Division Journal, 87:SA5:7, 1961.

55. Mohanka, S. "Theory of Multilayer Filtration", American Society of Civil Engineers - Sanitary Engineering Division Journal, 95:SA6:1079, 1969.

56. Sakthivadival, R., V. Thanikachalam, and S. Seetharaman. Headloss Theories in Filtration", Journal, American Water Works Association, 64:4:253, 1972.

57. Drewry, W.A. and R. Eliassen. "Virus Moment in Groundwater", Journal, Water Pollution Control Federation, 40:257, 1968.

58. Eliassen, R. "Clogging of Rapid Sand Filters", Journal, American Water Works Association, 33:5:926, 1941.

59. Kik, S. "Influence du Diame'tre des Collonnes Filtrantes sur las pirtes de Charge at sur LaDuire de la Filtration", Thesis presented to Ecole Polytechnique, at Montreal, Canada, in partial fulfillment for a Master of Science.

60. Kim, S. "The Effectiveness of a Contact Filter for the Removal of Iron from Ground Water", Report #IWR 13, Institute of Water Resources, University of Alaska, January 1971.

61. Leclerc, A. and T. Trudng. "Description and Retentivity of Filtration Materials", American Society of Civil Engineers - Sanitary Engineering Division Journal, 98:SA6:937, 1972.

INITIAL DISTRIBUTION

HQ USAF/PREE	1	SAMTEC/SEH	1
HQ USAF/PREVP	1	SAMSO/DEC	1
HQ USAF/PREVX	1	AMD/RDU	1
HQ USAF/SAFOI	1	ADTC/CSV	1
HQ USAF/RDPS	2	ADTC/DLODL	2
HQ USAF/SGPA	2	DDC/TCA	12
HQ COMD USAF/DEE	1	ARPA	1
AFLC/SGB	1	DEFENSE RESERCH & ENGRG/AD	1
AFLC/DEPV	1	OASD/(I&L)ES	1
AFLC/MAUT	1	USA ENVIR HYGN AG	1
AFLC/MMRF	1	CH OF ENGRG/ENGMC-RD	1
AFSC/DE	1	AFRCE/East Rgn	1
AFSC/SD	1	AFRCE/Cent Rgn	1
AFSC/DEV	1	AFRCE/West Rgn	1
AFSC/SGB	1	ENVIR PRT DIV, OP-45	1
AFSC/SGPE	1	NCEL, CODE 25111	1
AFSC/DLCAM	2	NAV AIR DEV CTR/MAE	1
ATC/DEPV	1	NAV SHIP R&D CTR/CODE 3021	1
AFIT/DEM	1	UNIV OF NEW MEXICO	1
AU/LDG	1	TECH TRANSFER STAFF (EPA)	1
AUL	1	OFFICE OF R&D (EPA)	1
AU/Surgeon	1	NATL SCI FNDTN	1
AFOSR	1	USA MED BIOENGRG R&D LAB	1
AFAPL	1	DET 1 HQ ADTC/PRL	2
AFAL/TSR	1	DET 1 HQ ADTC/WE	1
AFFDL/TST	1	DET 1 HQ ADTC/EC	1
AMRL/DAL	1	AFCEC/EV	1
AFML/DO	1	DET 1 HQ ADTC/EC	5
OEHL/CC	3		
OEHL/OL-AA	1		
OEHL/OL-AB	1		
AFWL/SUL	1		
AFCL/XOP	1		
USAFSAM/EDE	2		
AFRPL/Lib	1		
USA WW Exp Sta	1		
USA CERL	1		
USA Eng R&D Lab/MERDC	1		
Ch of R&D/DARD-ARE-E	1		
FTD/LGM	1		
AMRL/THE	1		
ASD/ENAMC	1		
ASD/ENESS	1		
ASD/ENFPA	1		
ASD/DEP	1		
ASD/SMKF	1		
AEDC/DEE	1		

(The reverse of this page is blank)